Journal of Cleaner Production 220 (2019) 212–224

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Managing the water-climate- food nexus for sustainable development in Turkmenistan

Weili Duan [a], Yaning Chen [a, *], Shan Zou [a, b], Daniel Nover [c]

[a] State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi, 830011, China
[b] University of Chinese Academy of Sciences, Beijing, 10049, China
[c] Department of Engineering, University of California – Merced, Merced, CA, 95340, USA

ARTICLE INFO

Article history:
Received 15 October 2018
Received in revised form
22 January 2019
Accepted 4 February 2019
Available online 7 February 2019

Keywords:
Water-climate–food nexus
Amu Darya River
Turkmenistan
Climate change
Scenarios

ABSTRACT

The water–climate-food security nexus is uniquely vulnerable in Central Asia, a region replete with transboundary water conflicts, shortages in land and water resources and high sensitivity to climate change. Using a water balance for the Amu Darya River Basin, we present a synthetic evaluation of future water use, crop yields, land and water productivities for the period 2016 to 2055 in Ahal, Dashoguz, Lebap, and Mary provinces in Turkmenistan. Modeled fut socio-economic scenarios include food security and diet change (FSD), export-oriented sustainable adaptation (ESA) and business as usual (BAU). Results show that water requirements and water deficits during growing seasons will exhibit a decreasing trend from 2016 to 2055 in most provinces under all three scenarios. Crop yields and land and water productivities will likely increase in the four provinces under both the FSD and ESA scenarios. Mary province had the highest mean income and losses of irrigated agriculture, with an annual average value of about 7×10^8 USD/year and 1.5×10^3 USD/year, respectively. Ahral province showed the largest annual mean land and irrigation water productivities for all three scenarios, up to about 800 USD/ha/year and 0.40 USD/m^3/year respectively. Results obtained from this study provide tools to assist resource managers to identify vulnerabilities in the nexus of water, land and climate to ensure food security, water management, and sustainable development.

© 2019 Elsevier Ltd. All rights reserved.

1. Introduction

Water, land and energy resources are critical as the foundation for food security, and ultimately for sustainable socio-economic development (Ellabban et al., 2014; Liu et al., 2018; Mohtar et al., 2019). Globally, water abstraction and water consumption for food production accounted for 70% and 90% of total withdrawals, respectively (AQUASTAT, 2016) and approximately 10% accounted for energy production and power generation in 2014 (IEA, 2016). Continuous climate change and population growth pose increasing challenges to food, water and energy security (DeNooyer et al., 2016; Godfray et al., 2010; Howells et al., 2013). Food demand for a growing global population is expected to increase by about 70% by 2050 and approximately triple by 2100 (Clay, 2011; Food and Agriculture Organization, 2009), coincident with a substantial increase in water and energy demand (Harvey et al., 2011; Smajgl et al., 2016). The pressures associated with population growth are and will continue to be compounded by climate change, which impacts water availability for food production, hydropower operations and in many other significant ways (Conway et al., 2015). Regional and global water scarcity due to population growth alone will be amplified by up to 40% due to climate change (Schewe et al., 2014), and agricultural production including crops such as maize, soybeans, wheat, and rice will decline by 8–24% of present-day totals under representative concentration pathway 8.5 (RCP 8.5) (Elliott et al., 2014). Identifying the linkages between water, energy, and food production offers the potential to simultaneously improve these complementary systems for human well-being and environmental sustainability, particularly in the context of population growth and climate change (Dai et al., 2018; Mohtar and Daher, 2015; Mortada et al., 2018).

Vulnerabilities in the water-climate–food security nexus are particularly acute in Central Asia for several reasons (Jalilov et al., 2016). First, the arid or semi-arid climate in Central Asia means that water is scarce and extremely valuable for approximately 70 million people (Bekturganov et al., 2016). Second, regional water

* Corresponding author.
E-mail address: chenyn@ms.xjb.ac.cn (Y. Chen).

https://doi.org/10.1016/j.jclepro.2019.02.040
0959-6526/© 2019 Elsevier Ltd. All rights reserved.

scarcity in trans-boundary river systems, such as the Amu Darya River, has been greatly aggravated by conflicting interests between upstream hydropower generation in Tajikistan and the downstream water needs of Turkmenistan and Uzbekistan for cotton, rice and wheat irrigation (Bernauer and Siegfried, 2012). Third, impacts from climate change are already being felt in Central Asia with rising temperature trends and changes in precipitation amounts and patterns, which are also likely to exacerbate water scarcity and food production (Aleksandrova, 2015; Farinotti et al., 2015). Finally, the total population in Central Asia has increased from 51 million in 1991 to over 70 million in 2016, which has accelerated the overexploitation of land and water resources to meet the food, water and energy demands of the population (Granit et al., 2012). These issues have left some Central Asian countries, such as Turkmenistan and Tajikistan, in a state of poverty. Sustainable approaches to water and land management as well as improvements in irrigation efficiency are all urgently needed to address energy and food security concerns in these countries and in the region (Bekchanov et al., 2016).

Like all Central Asian countries, Turkmenistan's arid climate makes it critically dependent on water. Turkmenistan's main water source is the Amu Darya River, which is a typical trans-boundary river between Turkmenistan and Uzbekistan, originating from the Pamir and Tien Shan Mountains. Land is also a scarce resource since about 80% of the country is covered by the Kara Kum desert (Kaplan et al., 2014). Unlike the upstream countries such as Tajikistan, energy is not a major problem in Turkmenistan. Limited water and land resources, low irrigation efficiency, poor drainage systems, and a rapidly growing population and economy are plaguing the country and driving interest in research to identify sustainable resource management strategies (Bekchanov, 2014; Bekchanov et al., 2016). The impacts of climate change and population growth on water resources (Kostianoy et al., 2011) and food production (Stanchin and Lerman, 2017) have been emphasized in the pursuit of appropriate adaptation measures (Jalilov et al., 2018), but projections of future changes in water requirements and food production under different socio-economic development scenarios are not well developed (Jalilov et al., 2016).

This study uses climate projections to analyze the water balance for the Amu Darya River Basin and evaluate future water use, crop yields, land and water productivities for the period 2016 to 2055 in Turkmenistan. We also explore the potential for future climate impacts on the water–food security nexus in Turkmenistan. Specifically, this study addresses (1) How climate change affects the runoff of the Amu Darya River and water resources can be estimated in Turkmenistan from 2016 to 2055; (2) How standard net crop water requirements under climate change; and (3) How future water requirements and water deficits for irrigated lands, agricultural yields from several major crops, and land and water productivities under different development scenarios in Turkmenistan can be evaluated. Little previous research addresses these issues. In particular, our study adds insights into: (1) the water– climate–food security nexus under different future socio-economic development scenarios in Turkmenistan. Results obtained in this study will help understand the interconnections between climate change, water resources, and food production in this country. and (2) water requirements and deficits, agricultural yields from several major crops, land and water productivity from 2016 to 2055 under three socio-economic scenarios. Results provide essential information for effective water resources management and agricultural development in Turkmenistan.

We present study area, datasets and methodology in the next section. Results of future water resources, water requirements and deficits, agricultural yields, and land and water productivity are presented in Section 3, followed by discussions (Section 4), and conclusions (Section 5).

2. Data and methods

2.1. Study area

The Amu Darya River, the largest river in Central Asia, originates from the Pamiro-Alai Mountains (elev. 4900 m) on the border between Tajikistan and Afghanistan, and flows 2540 km northwestward before emptying into the Aral Sea (Fig. 1). Its drainage basin lies between 54°E and 75°E and 33°N and 47°N, covering most regions of Tajikistan, Uzbekistan and Turkmenistan, and small regions of Afghanistan, Kyrgyzstan and Iran, with a total area of about 1.33×10^6 km^2 (Fig. 1). Seventy percent of the Amu Darya River originates from two tributaries: the Vakhsh River and the Pyanj River. The remaining water resources are from the Kafirnigan, Surkhandarya, and Kunduz Rivers. Runoff from these rivers originates primarily from rainfall and the melting of snow and ice at high elevations, which are vulnerable to climatic change (Li et al., 2017; Malsy et al., 2012; Sorg et al., 2012). Meanwhile, rapid economic development and population growth in the basin are driving significant changes to landcover and resource use (e.g. Rogun reservoir) and changing water availability and patterns of water demands (Rakhmatullaev et al., 2017).

Turkmenistan lies in the lower and middle reaches of the Amu Darya River and is mainly covered (80%) by the Karakum Desert (Fig. 1). The Amu Darya River is the main water source for all agricultural and non-agricultural uses in Turkmenistan, accounting for more than 80% of total fresh water resources. According to the water allocation agreements between all Central Asian countries (Protocol No. 566), Turkmenistan's share is about 35.8% of the total runoff from the Amu Darya River (Kostianoy et al., 2011). More than 90% of the water is consumed by irrigated agriculture (e.g., for cotton, wheat, rice, vegetables, fruits, and cucurbits) through an integrated water management system (e.g., the Karakum Canal), mainly in our focus provinces of Ahal, Dashoguz, Lebap and Mary provinces.

2.2. Methodology

2.2.1. The Aral Sea Basin management model and calculation process

The Aral Sea Basin management model (ASBmm) developed by the Science Information Center of the Interstate Coordination Water Commission of Central Asia (SIC ICWC) and UNESCO-IHE was applied to calculate the future water balance and water allocation for the Amu Darya River Basin (De Schutter, 2008; Merks, 2018). Its objective is to develop an integrated assessment method for sustainable development in the Aral Sea Basin, considering socio-economic, environmental, energy and climatic factors, optimization and trade-off solutions. The ASBmm contains two separate models for the Amu Darya and the Syr Darya river basins, and each basin in the simulation model is divided into planning zones (PZs) based on administrative boundaries already existing in the region. Each model consists of four main modules including the flow formation model, the water allocation model (WAm), the planning zone model (PZm), and the socio-economic model. Each planning zone (PZ) is an individual region with its own water balance and water use activities which generally contain domestic, industrial and agricultural water use. The water balance accounts for almost all hydrological processes, including evaporation, groundwater in- and outflow, seepage, return flow from the PZs, withdrawal by PZs and inflows and discharges into other components (see detailed computing processes at http://www.cawater-info.net/).

The hydrological scheme of the Amu Darya River Basin and the

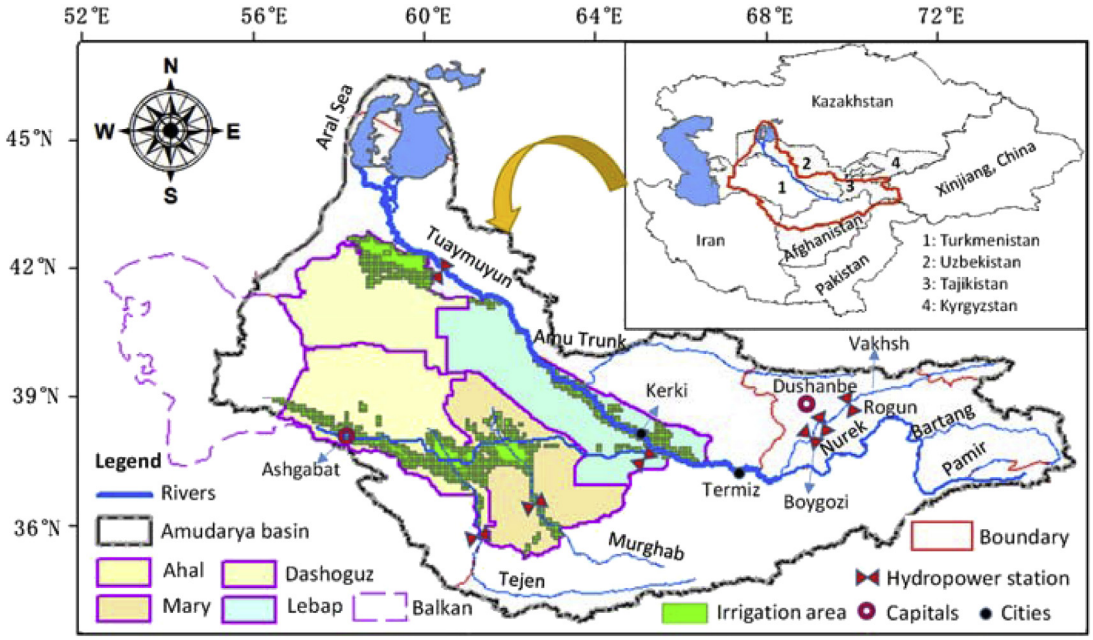

Fig. 1. Location of the Amu Darya River Basin, river systems, and Turkmenistan.

PZs for the four provinces in Turkmenistan are shown in Fig. 2 (green boxes). Fig. 2 also shows the main tributaries in the Pyanj River, the Vakhsh River, the Kafirnigan River, and the Surkhandarya River. The PZm computes the water balance in each water-management political province under different climatic, socio-economic and water-management scenarios in connection with a river network, including water balances of irrigated areas, estimation of return water (CDF), and calculation of agricultural output losses (in case of water shortages) on the basis of local resources (e.g., groundwater) and flow regulation by local reservoirs. The PZm is used here to calculate water requirements and evaluate the land and water productivity for the four provinces of interest (Ahal, Dashoguz, Lebap and Mary) in Turkmenistan.

Fig. 3 shows the framework for calculating water requirements, water deficits, crop yields, agricultural output losses (in case of water shortage), and land and water production for the four provinces in Turkmenistan. Here, future water balance and water allocation from transboundary rivers were taken from an existing ASBmm model (De Schutter, 2008; Merks, 2018). This study employs a regional climate model, a projection of the greenhouse gas concentration scenario of Coupled Model Intercomparison Project Phase 3 (CMIP3) SRES-A1B for Central Asia, to evaluate the possible impacts of climate changes on water resources (REMO-0406 - detailed information at https://www.remo-rcm.de/). Three socio-economic scenarios were employed, including the food security and diet change (FSD), export-oriented sustainable adaptation (ESA), and business as usual (BAU) scenarios. BAU means that there is "no change" in the future; FSD aims for maximum production for food self-sufficiency in line with population growth; ESA aims for maximum food exports with a food self-sufficiency at 80% in the future. In these three scenarios, the change of population from 2016 to 2055 was based on demographic data over the last decade for each planning zone. For the BAU scenario, the future cropping patterns and yield output were predicted based on trends of the last decade. Long-term target parameters adopted in the National Program of Turkmenistan on Socio-Economic Development during the period 2011–2030 were used to construct the future cropping patterns and yield output for both the FSD and ESA scenarios.

The water scenario was selected via the coefficient of provision of water withdrawal limit from transboundary sources. For example, 50% was chosen in this study, which means 50% of river discharge from the Amu Darya River could be taken during the growing season. An innovation scenario was determined assuming development of innovative and efficient irrigation methods. Water delivery, crop yields (cotton, wheat and rice) and water productivity were used as major indicators of performance for the irrigation system of the basin. Table 1 shows the reduction of water consumption and increase in production based on innovative water-saving technologies, suggesting substantial changes in water-use efficiency and food production after adoption. Under the above scenarios, future water requirements and water deficits for irrigated lands, agricultural yields from several major crops, land productivity (gross production per ha irrigated area), and water productivity (gross production per m^3 water intake) in Turkmenistan were calculated according to the following equations:

(1) The monthly standard net crop water requirements in planning zones are described by Equation (1):

$$W_{zirn}(dt) = H_z * \sum wzm_r(dt) * Hz_r \quad (1)$$

where t is the time, z is the set of planning zones (here we have four planning zones), r is the set of crops in planning zones, W_{zirn} is the monthly standard net crop water requirements in planning zones (10^6 m^3), dt is the H_z is the total irrigated area of the four provinces (10^3 ha), $wzm_r(dt)$ is the average annual standard of irrigation for crop r (m^3/ha), and Hz_r is the fraction of area under crop r in each province out of the total irrigated area of the four provinces. The predicted standard irrigated agricultural water demand, including losses in the irrigation network, is estimated as:

$$W_{zir}(\mathrm{dt}) = W_{zirn}(\mathrm{dt}) * \frac{\mathrm{ET(dt)} - \mathrm{pzef(dt)}}{ETm(dt) - pzmef(dt)} \quad (2)$$

where $W_{zirn}(\mathrm{dt})$ represents the monthly standard net crop water

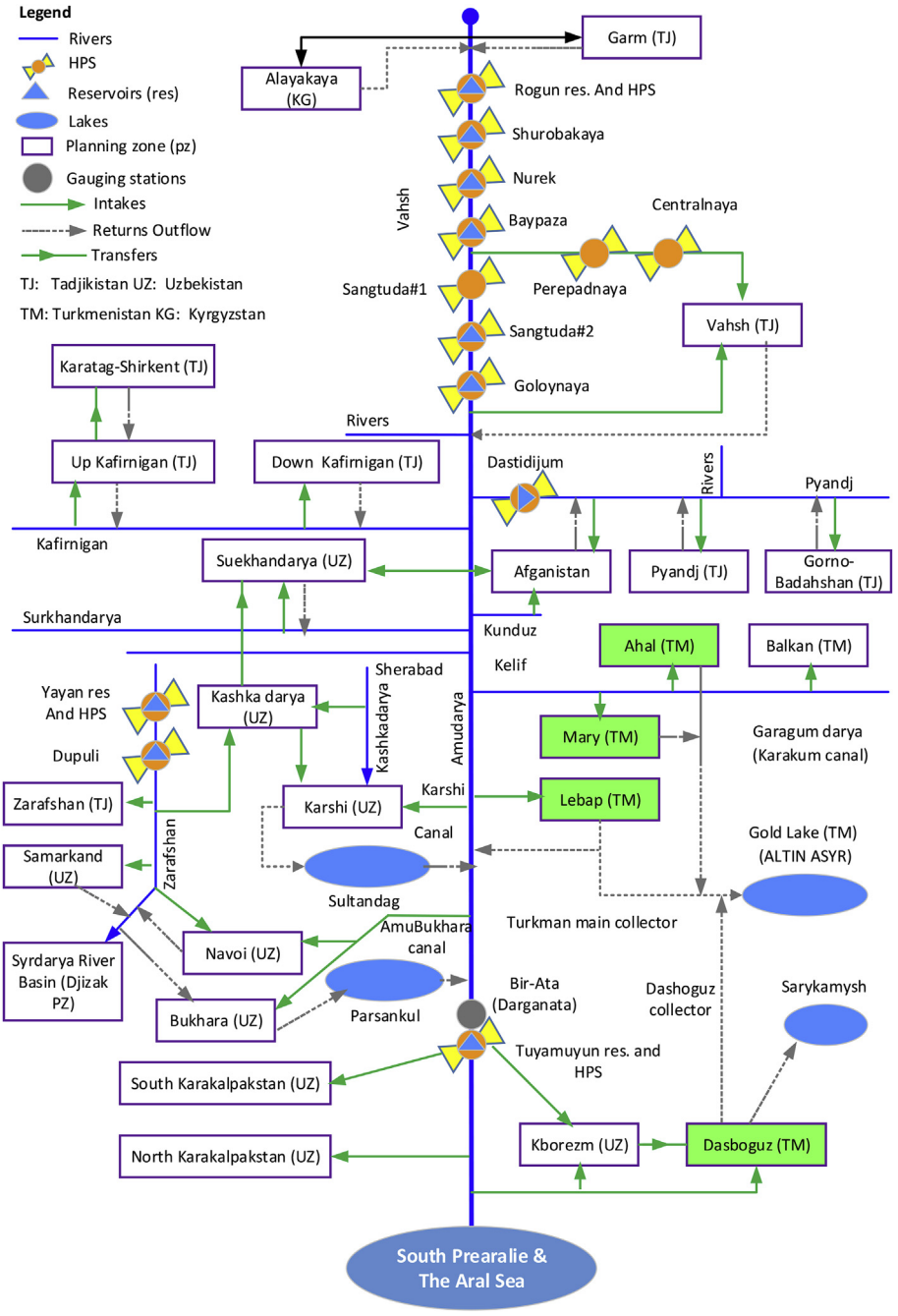

Fig. 2. Hydrological scheme of the Amu Darya River Basin and planning zones for four provinces (green background) in Turkmenistan (Source from http://www.cawater-info.net/). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

requirements in planning zones (10^6 m^3), $ET(dt)$ is the predicted reference evapotranspiration calculated by the Penmann-Monteith formula (FAO publication 56), $ETm(dt)$ is the average annual reference evapotranspiration, and $pzmef(dt)$ is the average annual effective precipitation for each province. The average annual reference evapotranspiration $ETm(dt)$ is estimated as:

$$ETm(dt) = 0.00144*(25 + T(dt))^2*(100 - Lm(dt)) \quad (3)$$

where $T(dt)$ is the predicted average monthly temperature (K), and $Lm(dt)$ is the average monthly humidity (%).

(2) Output losses calculate the average crop yield losses in case of water shortage for crop r for each province (δYz_{gr}, %) according to:

$$\delta Yz_{gr} = s_r*(100 - \alpha)*\eta*wnz_r/ET_r \quad (4)$$

where s_r is the irrigation area for crop r, α is the coefficient of irrigation norm (for a season) reduction under shortage, η is the coefficient of efficiency of the irrigation network in planning zones. Variable wnz_r is the predicted necessary irrigation norm (for a season) accounting for climate change for crop r in the future (m^3/ha), and ET_r is predicted seasonal evapotranspiration of crop r over a season (m^3/ha). Of them, α is calculated as:

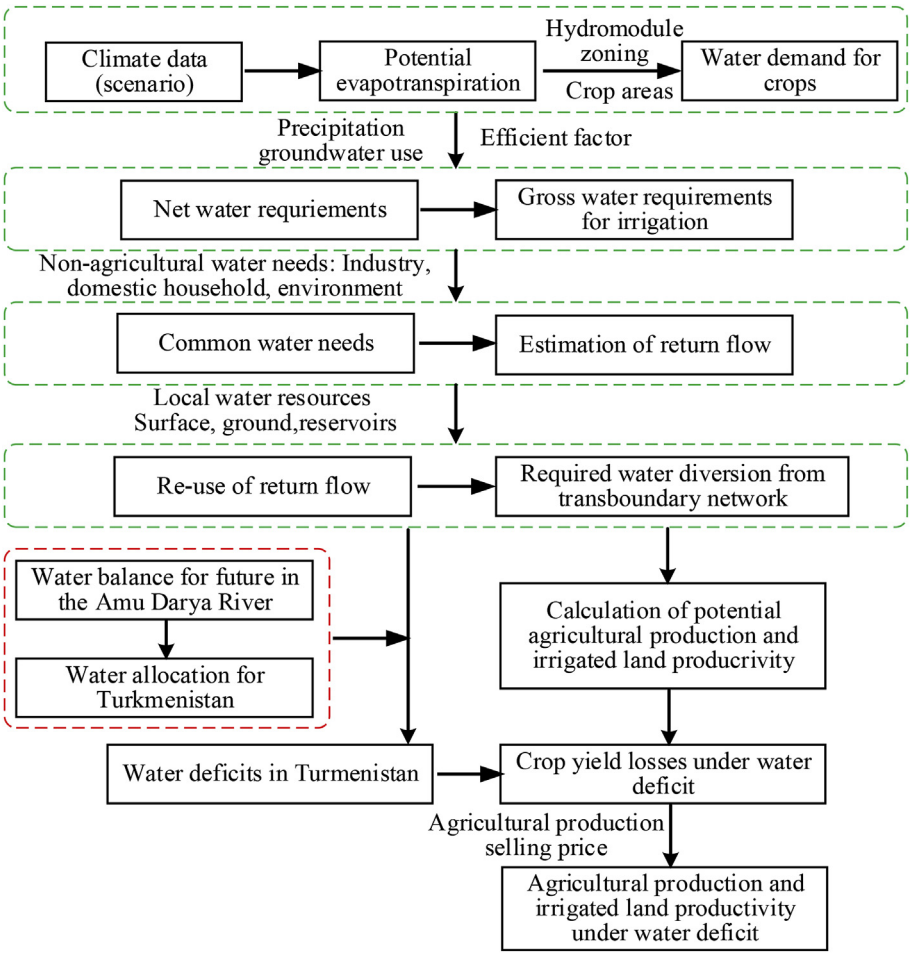
Climate data (scenario)
Potential evapotranspiration
Hydromodule zoning
Crop areas
Water demand for crops
Precipitation groundwater use
Efficient factor
Net water requriements
Gross water requirements for irrigation
Non-agricultural water needs: Industry, domestic household, environment
Common water needs
Estimation of return flow
Local water resources Surface, ground,reservoirs
Re-use of return flow
Required water diversion from transboundary network
Water balance for future in the Amu Darya River
Water allocation for Turkmenistan
Calculation of potential agricultural production and irrigated land producrivity
Water deficits in Turmenistan
Crop yield losses under water deficit
Agricultural production selling price
Agricultural production and irrigated land productivity under water deficit

Fig. 3. Procedure for calculating water requirements and irrigated agriculture productivity.

Table 1
Reduction of water consumption (%) and increase in production (%) based on innovative water-saving technologies.

Crops	Drip irrigation technology		Other innovative technologies	
	Reduction of water consumption (%)	Increase in production (%)	Reduction of water consumption (%)	Increase in production (%)
Cotton	52	45	20	10
Cereals (wheat, rice, maize)	–	–	20	10
Potatoes, melons and vegetables	55	65	20	10
Fruits and grapes	40	60	–	10

$$\alpha = 100*Wlz / Wzdir \quad (5)$$

where *Wlz* is the irrigation water supply limit for a season (10^6 m^3), *Wzdir* is the irrigated agriculture water demand, including losses in the irrigation network (within the boundaries of planning zones) over a season (10^6 m^3).

And wnz_r can be calculated as:

$$wnz_r = wmz_r * (ET_0 - pzef)/(ET_m - pzmef) \quad (6)$$

where wmz_r is the average annual irrigation norm (for a season) for crop r (m^3/ha), ET_0 is the predicted reference evapotranspiration calculated by the Penmann-Monteith formula (FAO publication 56), *pzef* is the predicted effective precipitation rate over the growing season for planning zones, $ET_m$is the annual predicted reference evapotranspiration, and *pzmef* is the average annual effective precipitation rate over the growing season for planning zones.

The predicted seasonal evapotranspiration of crop r (ET_r) is estimated as:

$$ET_r = \sum k_r(t) * ET \quad (7)$$

where *ET* is the predicted reference evapotranspiration, and $k_r(t)$ is the average monthly crop coefficient for crop r.

2.2.2. Datasets

The model output multiple projections that were processed to develop future land and water indicators. Most of the original datasets were obtained from the Official Statistics of Turkmenistan (http://www.stat.gov.tm/), the World Bank Group (https://data.worldbank.org/country/turkmenistan), and the Portal of Knowledge for Water and Environmental Issues in Central Asia (http://

www.cawater-info.net/), which contain historical population data, summary of water resources, industrial water usage, climate data, Amu Darya discharge data, socio-economic data. for the time period 2000 to 2014. Other data were obtained from national or provincial energy strategy documents from Turkmenistan (Garabayeva, 2012).

2.2.3. Statistical analysis

The Mann-Kendall test was applied to evaluate trends in water requirements, food production, and socio-economic impacts from land production (gross production per ha irrigated area) and water production (gross production per m^3 water intake) under different scenarios. Given a dataset consisting of T values with sample size n, the Mann-Kendall S Statistic is computed as follows (Kendall, 1975; Mann, 1945):

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign(T_j - T_i) \tag{8}$$

$$sign(T_j - T_i) = \begin{cases} 1 & if\ T_j - T_i > 0 \\ 0 & if\ T_j - T_i = 0 \\ -1 & if\ T_j - T_i < 0 \end{cases} \tag{9}$$

where n is the sample size, T_j and T_i represent the variability of the above indicators at times j and i ($j > i$). Because the sample is the annual simulation for a total of 40 years (2016–2055) in this study, the sample size (n) is 40. As indicated in Mann (1945) and Kendall (1975), when $n \geq 10$, S is approximately normally distributed with mean $E(S) = 0$ and variance (σ^2), which can be calculated as follows:

$$\sigma^2 = \frac{n(n-1)(2n+5) - \sum t_i(i)(i-1)(2i+5)}{18} \tag{10}$$

where $E(S)$ is the mean value of the S statistic, t_i denotes the number of ties to extent i. The summation term in the numerator is only used if the data series contains tied values. Finally, the standard test statistic Z is calculated as follows:

$$Z = \begin{cases} \frac{S-1}{\sigma} & for\ S > 0 \\ 0 & for\ S = 0 \\ \frac{S+1}{\sigma} & for\ S < 0 \end{cases} \tag{11}$$

The test statistic Z is used as a measure of significance of trend (e.g. see (Duan et al., 2017a; Yue et al., 2002), which is used to test the null hypothesis (H_0). When $|Z|$ is greater than $Z_{\alpha/2}$, where α is the chosen significance level (e.g., 5% with $Z_{0.025} = 1.96$), the null hypothesis is invalid implying that the trend is significant.

3. Results

3.1. Future river runoff

Fig. 4a shows dynamics of predicted annual runoff of the Amu Darya River under the REMO 0406 scenario, revealing that annual runoff would exhibit a slight increasing trend with the Z value at 0.90 (not significant) from 2016 to 2055. The highest annual runoff is 104×10^9 m^3/year in 2026, and the average annual runoff is 66.77×10^9 m^3/year, which is lower than the average one (approximately 68.45×10^9 m^3/year) for the period 1933–2015, revealing a decline of 1.68×10^9 m^3/year under climate change. As in the case of main tributaries, the average annual runoff for Pyandj, Vakhsh, Kafirnigan, Surkhandarya, and Kunduz Rivers during the period 2016–2055 are about 34.50×10^9, 19.12×10^9, 5.34×10^9, 3.42×10^9, and 4.39×10^9 m^3/year, respectively. Compared with the average annual runoff from 1933 to 2015, the Pyandj River had the largest decline during the period 2016–2055 under the REMO 0406 scenario, 0.86×10^9 m^3/year, followed by the Vakhs (0.6×10^9 m^3/year), the Kafirnigan (0.17×10^9 m^3/year), the Surkhandarya (0.03×10^9 m^3/year), and the Kunduz (0.02×10^9 m^3/year).

Although changes of annual runoff from 2016 to 2055 are small, the monthly changes are large. River runoff is expected to decrease in June–August, and the runoff will increase in April and some months during the growing season. Fig. 4b clearly illustrates the reduction of river runoff (against the average monthly flow for the period 1933–2015) in June–August, suggesting a significant increasing trend for all three months, with the Z values at 5.11, 5.64 and 6.31, respectively. Of them, the reduction of river runoff in July is the largest, 1.35×10^9 m^3/year, followed by June (0.69×10^9 m^3/year) and August (0.46×10^9 m^3/year). In 2055, the reduction of river runoff will be 1.32×10^9 m^3 in June, 2.77×10^9 m^3 in July, and 0.64×10^9 m^3 in August. All runoff series are used as a basis for numerical experiments for water requirements.

3.2. Water requirements and deficits during growing season

Fig. 5a and b shows the time series of water requirements and water deficits during the growing season (April–September) from 2016 to 2055 in Turkmenistan. The water requirements under the FSD and ESA scenarios were clearly greater than the water requirements under the BAU scenario, and the difference between them increased continuously, 4.40×10^9 m^3/month in 2055. Similarly, both the FSD and ESA scenarios had larger water deficits compared to the BAU scenario. The estimated water shortages were 7.88×10^9 m^3, 7.47×10^9 m^3, and 4.33×10^9 m^3 in 2055 under the ESA, FSD, and BAU scenarios, respectively.

Fig. 5c and d shows the Mann-Kendall test results (Z value) for water requirements and water deficits during the growing season from 2016 to 2055 for all three scenarios in Turkmenistan and its four provinces. Except for the Lebap and Mary provinces, a decreasing trend was found for water requirements under all scenarios in the other provinces. Among them, the BAU scenario had a significant decreasing trend at the 95% confidence from 2016 to 2055 in the four provinces (Fig. 5c). Water requirements in Lebap province under the ESA scenario showed a significant increasing trend indicating that water deficits during the growing season increased (95% confidence - Fig. 5d). As with water requirements, water deficits exhibited a significant decreasing trend under the BAU scenario from 2016 to 2055 in Turkmenistan. A significant increasing trend was also found for water deficits under both the FSD and ESA scenarios in Mary province.

Fig. 6 shows the mean annual water requirements and annual water deficits during the growing season by province for all three scenarios, from 2016 to 2055. As can be seen in Fig. 6, the estimated average water requirements for the three scenarios was largest for Dashoguz province, at 3.90×10^9 m^3, followed by Ahal, Mary and Lebap provinces. Except for Ahal province, the largest water requirements were found for the FSD scenario in the other provinces, followed by the ESA scenario and the BAU scenario. In terms of water deficits, Dashoguz province had the highest average estimate of all three scenarios, at 2.50×10^9 m^3, while the value decreased to 0.60×10^9 m^3 in Mary province. This may reflect less irrigated areas and local water resources in Mary province compared with Ahal province. As with water requirements, the FSD scenario showed the largest water deficits of all provinces, especially Ahal (2.50×10^9 m^3), followed by the ESA scenario and the BAU scenario.

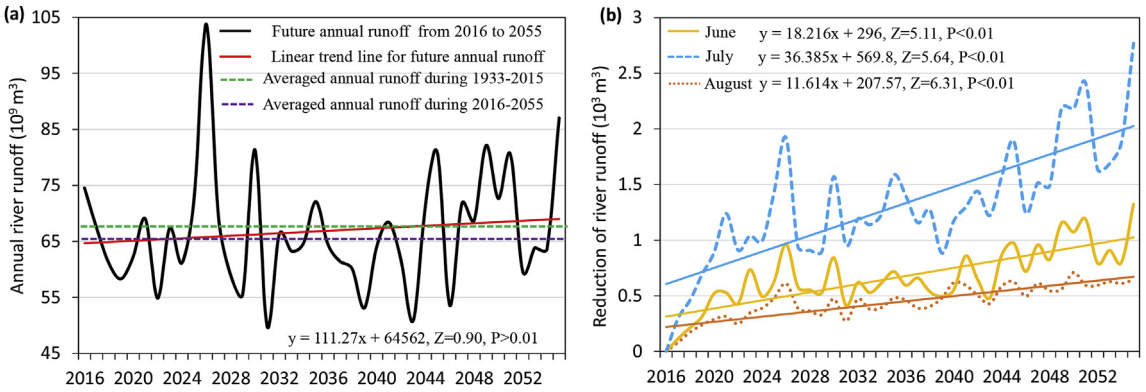
(a)
Future annual runoff from 2016 to 2055
Linear trend line for future annual runoff
Averaged annual runoff during 1933-2015
Averaged annual runoff during 2016-2055
y = 111.27x + 64562, Z=0.90, P>0.01
Annual river runoff (10⁹ m³)
(b)
June y = 18.216x + 296, Z=5.11, P<0.01
July y = 36.385x + 569.8, Z=5.64, P<0.01
August y = 11.614x + 207.57, Z=6.31, P<0.01
Reduction of river runoff (10³ m³)

Fig. 4. (a) Annual runoff of the Amu Darya River under the REMO 0406 scenario from 2016 to 2055; (b) Reduction of runoff caused by climate change (REMO 0406 scenario). The red line is the linear trend line, and the dashed lines are the average annual river runoff for history (1933–2015) and future (2016–2055). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

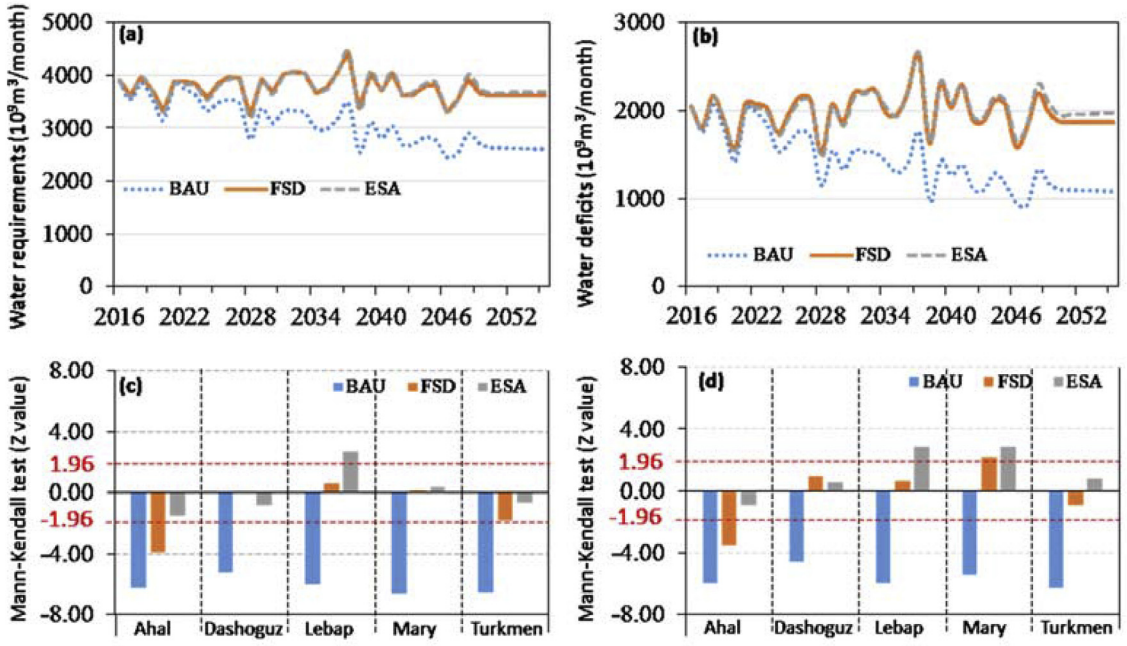

Fig. 5. Time series of (a) water requirements (10^9 m^3/month) and (b) water deficits (10^9 m^3/month), (c) Mann-Kendall test (Z value) of water requirements, and (d) Mann-Kendall test (Z value) of water deficits for growing season under three scenarios (BAU, FSD, and ESA) from 2016 to 2055.

3.3. Agricultural productivity

As expected, the results of agricultural yields shown in Figs. 7 and 8 demonstrate considerable temporal variations. Most crops in some provinces show increases in production, while others see declines. Production of seven major crops including cotton, wheat, rice, maize, vegetables, orchards, and forage, were predicted to increase under both the FSD and ESA scenarios for all four provinces during the period 2016–2055, and most of them were significant at the 95% confidence level (Fig. 8). For example, by 2055, cotton yields are expected to increase to 2.55 t/ha, 2.29 t/ha, 3.08 t/ha, 4.26 t/ha under the ESA scenario in Ahal, Dashoguz, Lebap, and Mary provinces, respectively, and orchard yields were predicted to increase to 13.27 t/ha, 23.61 t/ha, 5.24 t/ha, 10.18 t/ha under the ESA scenario in Ahal, Dashoguz, Lebap, and Mary provinces, respectively. These estimated productivities are much larger than the yields under the BAU scenario in 2055 (Fig. 7 and Table 2). As shown in Figs. 7 and 8, we can also see that the variation in yield between different years and between different provinces seems to be quite significant. The main reason is the difference of various climatic factors in different regions, including the different water availability in them.

Under the BAU scenario, by contrast, a significant decreasing trend was found for maize yields in Ahal province, wheat and vegetable yields in Dashoguz province, and vegetables, orchards and forage yields in Mary province. Maize yields are expected to decrease to 9.19 t/ha in 2055 in Ahal province, and vegetable yields are expected to decrease to 9.37 t/ha in 2055 in Dashoguz province. The vegetables, orchards, and forage yields are also predicted to decrease to 19.71, 3.18, and 8.92 t/ha in 2055, respectively. Except for rice, Figs. 7 and 8 also show that Lebap province is the only province with a significant increasing trend for most major crops for all three scenarios.

Fig. 7 and Table 2 also clearly show that Mary province will have higher yields for most crops including cotton, wheat, rice, vegetables, and forage under the three scenarios, and lower yields for

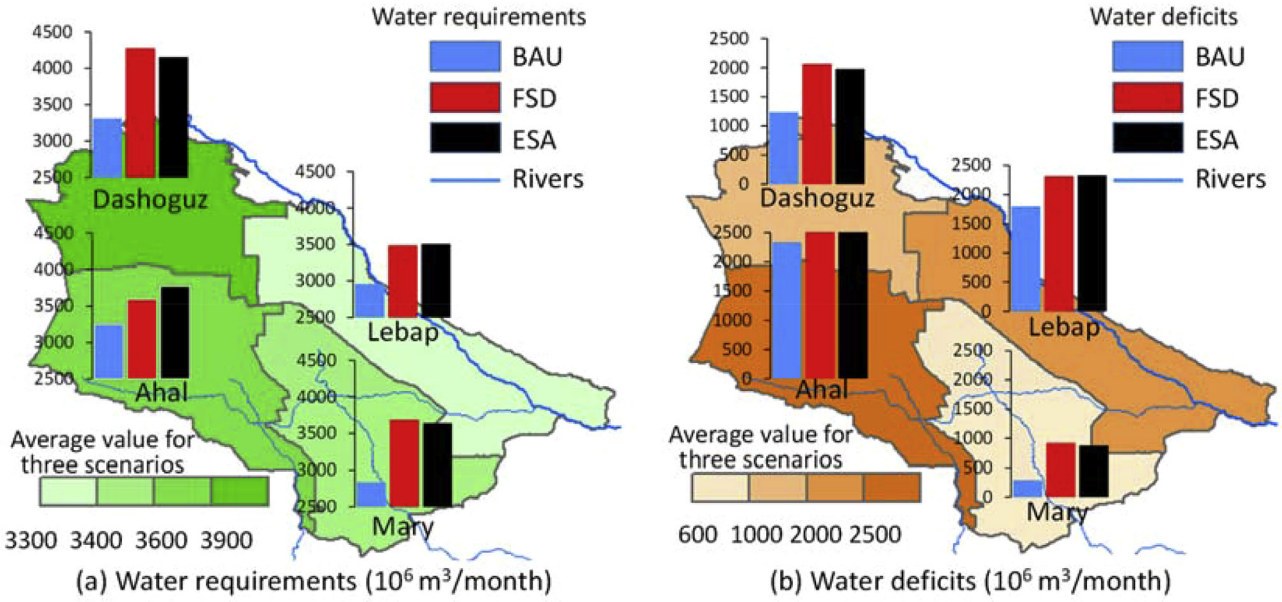

Fig. 6. The annual mean (a) water requirements (10^6 m^3/month) and (b) water deficits (10^6 m^3/month) during growing season under BAU, FSD, and ESA scenarios in Turkmenistan and its four provinces from 2016 to 2055.

wheat, rice, and forage in Ahal province. Among them, cotton yields in Mary province were about double those in Ahal province, and wheat and forage were about three times and five times respectively. The sharp increase in forage may reflect a significant increase in livestock in this province. Almost all rice in Turkmenistan is produced in Mary province (Fig. 7c), which is estimated to increase to 12.32, 17.14, and 14.24 t/ha by 2055 under BAU, FSD, and ESA scenarios, respectively. Ahal province had the largest productivity of maize for Turkmenistan, with a value of 9.19, 28.06, and 20.58 t/ha in 2055 under the BAU, FSD, and ESA scenarios, respectively.

3.4. Land and water productivity

There is evidence that farmers/irrigators with more productive land are likely to suffer more in case of water shortage than farmers/irrigators with less productive land (Akhtar et al., 2013). National water allocation should therefore first meet the water demand of water users who have more productive land. Fig. 9 shows the estimated annual values of the revenue of irrigated agriculture (Millions of USD), revenue losses in irrigated agriculture (USD), land productivity (USD/ha), and irrigation water productivity (USD/m^3) for the four provinces in Turkmenistan from 2016 to 2055, showing a significant increasing trend for all four provinces under the FSD and ESA scenarios. Fig. 9 and Table 3 show that (1) in Mary province, the estimated annual revenue from irrigated agriculture increased from 6.55×10^8 USD in 2015 to 11.80×10^8 USD and 14.20×10^8 USD in 2055 under the FSD and ESA scenarios respectively, and the estimated annual land productivity increased from 1125.28 USD/ha in 2015–2813.67 USD/ha and 3373.65 USD/ha in 2055, (2) in Ahal province, the annual revenue losses in irrigated agriculture is predicted to increase from 283.54 USD in 2015 to 1083.19 USD and 1595.17 USD in 2055 under the FSD and ESA scenario respectively, and the estimated annual irrigation water productivity is predicted to increase from 704.91 USD/ha in 2015 to 1469.6 USD/ha and 1968.02 USD/ha in 2055.

Fig. 9 and Table 2 also clearly indicate that the BAU scenario had the lowest value for all land and water productivity indictors. A decreasing trend was also found for the estimated annual revenue losses in irrigated agriculture in Mary province from 2016 to 2055 under the BAU scenario. In contrast, the ESA scenario had the largest value for all land and water productivity indictors, suggesting that both incomes and losses from irrigated agriculture will likely reach the highest level under export-oriented sustainable adaptation in Turkmenistan.

Fig. 10 shows the estimated averaged annual revenue of irrigated agriculture (USD 10 Million), revenue losses in irrigated agriculture (USD), land productivity (USD/ha), and irrigation water productivity (USD/m^3) under the BAU, FSD, and ESA scenarios for four provinces in Turkmenistan from 2016 to 2055. The revenue loss depends on the water availability under different scenarios (see Fig. 5), which is equal to the yield loss (t) multiplied by price for agricultural crops. Fig. 5b shows changes of water deficits in the future, which could be used to calculate the yield loss for the BAU, FSD, and ESA scenarios. Mary province had the highest mean incomes from irrigated agriculture for the three scenarios, at 7×10^8 USD/year during the period 2016–2055, followed by Dashoguz, Lebap, and Ahal provinces, clearly suggesting the rank of agricultural incomes for different provinces in Turkmenistan in the future. This spatial distribution was consistent with that of the average revenue losses of irrigated agriculture, revealing that the provinces with higher income from irrigated agriculture will suffer greater revenue loss in case of water shortage. Ahal province had the highest land productivity and irrigation water productivity (Fig. 10c and d), at 800 USD/ha/year and 0.40 USD/m^3/year respectively, followed by Lebap province. Fig. 10 also clearly illustrates that the ESA scenario (black) had the highest estimated value for all four land and water productivity indictors, as illustrated in Fig. 9 and Table 2.

4. Discussion

Climate change will likely exacerbate the challenges of meeting needs of the water-climate-food security nexus in Turkmenistan. Climate change, including changes in precipitation patterns and rising temperatures, is expected to increase the frequency of climate-related shocks in Turkmenistan, which will put increasing pressure on water supply and food production. On the one hand, based on the simulation of the REMO 0406 scenario, a significant

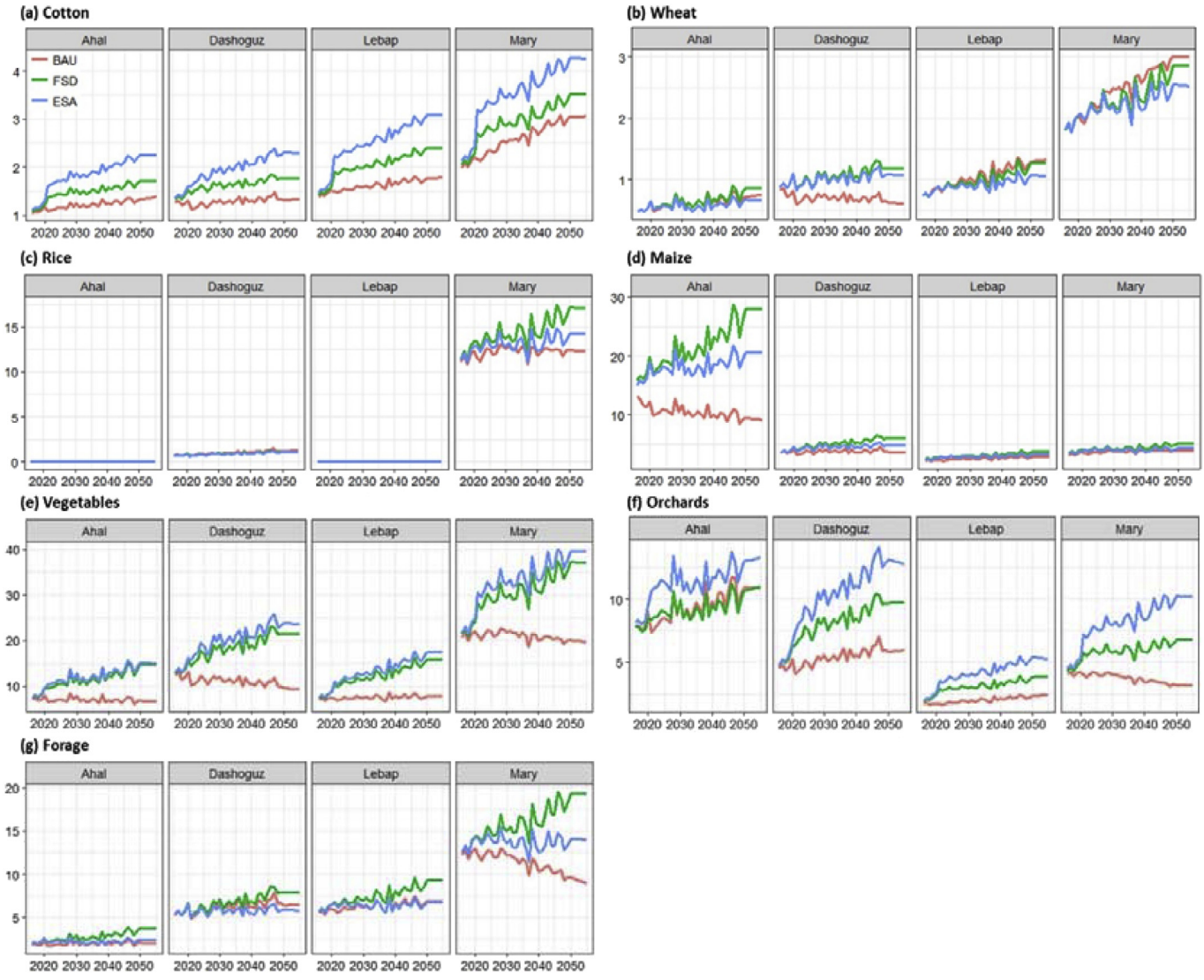

Fig. 7. Crop yield (ton/ha) of (a) cotton, (b) wheat, (c) rice, (d) maize, (e)vegetables, (f) orchards, and (g) forage under BAU, FSD, ESA scenarios in four provinces of Turkmenistan from 2016 to 2055.

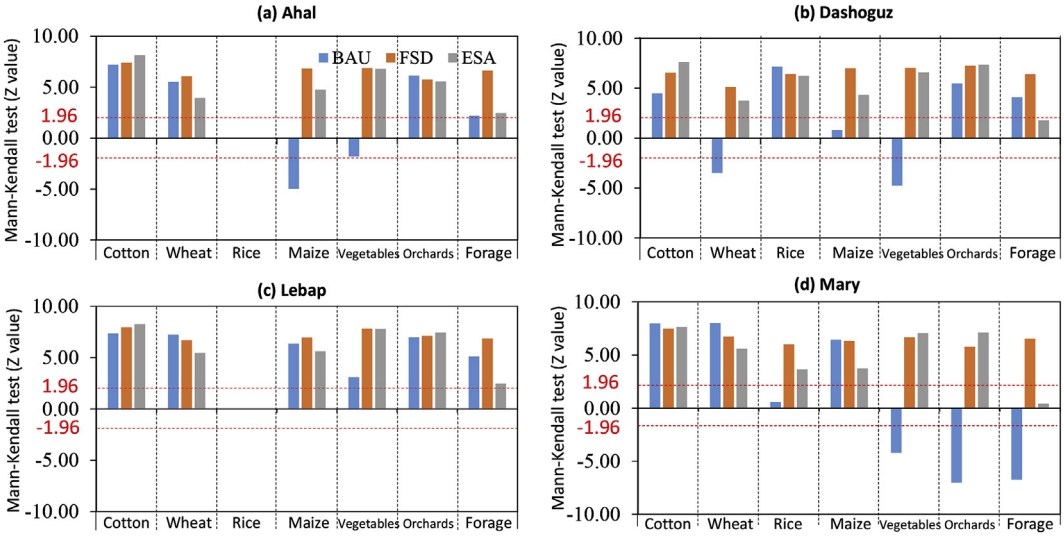

Fig. 8. Mann-Kendall test (Z value) for six types of corps in (a) Ahal, (b) Dashoguz, (c) Lebap, and (d) Mary from 2016 to 2055.

Table 2
Crop yields in the four provinces in Turkmenistan under different scenarios.

Province	Scenario	BAU		FSD		ESA	
	Year	2020	2055	2020	2055	2020	2055
Ahal	Cotton	1.17	1.38	1.23	1.71	1.32	2.25
	Wheat	0.66	0.75	0.66	0.86	0.66	0.67
	Rice	0	0	0	0	0	0
	Maize	12.3	9.19	19.94	28.06	18.97	20.58
	Vegetables	7.94	6.62	9.45	14.68	9.81	15
	Orchards	9	10.87	8.46	10.96	9.41	13.27
	Forage	2.13	2	2.61	3.66	2.57	2.37
Dashoguz	Cotton	1.29	1.33	1.54	1.76	1.61	2.29
	Wheat	0.82	0.61	1.1	1.19	1.1	1.08
	Rice	0.91	1.3	0.9	1.11	0.86	1.06
	Maize	4.15	3.66	4.53	6.01	4.52	4.83
	Vegetables	13.19	9.37	15.68	21.48	16.23	23.61
	Orchards	5.24	5.94	6.34	9.75	6.58	12.76
	Forage	6.5	6.49	6.66	7.86	6.55	5.78
Lebap	Cotton	1.51	1.78	1.57	2.39	1.67	3.08
	Wheat	0.87	1.33	0.84	1.27	0.84	1.06
	Rice	0	0	0	0	0	0
	Maize	2.37	2.92	2.79	3.84	2.65	3.3
	Vegetables	7.38	7.72	8.55	15.96	8.59	17.52
	Orchards	1.72	2.43	2.39	3.89	2.54	5.24
	Forage	5.97	6.81	6.49	9.27	6.4	6.71
Mary	Cotton	2.2	3.06	2.27	3.51	2.43	4.26
	Wheat	2.06	3	2.05	2.86	2.05	2.53
	Rice	12.32	12.32	13.41	17.14	12.87	14.24
	Maize	3.6	3.97	4.06	5.16	3.87	4.36
	Vegetables	22.07	19.71	23.93	37.07	24.73	39.62
	Orchards	4.24	3.18	4.96	6.82	5.34	10.18
	Forage	12.97	8.92	14.38	19.3	14.17	13.99

increasing trend was detected in future temperature, at 0.51 °C/decade, causing a decreasing trend in glaciers and snow cover. Climate warming will also drive concurrent changes in the effective temperature (accumulated temperature), leading to shifts in crop phenology (Chmielewski et al., 2004; Peã Uelas et al., 2009). For example, rising temperatures may shorten the growing season for cotton and therefore reduce water requirements (Wang et al., 2008). With increasing temperatures, however, the rate of evaporation along the Karakum Canal and other conveyance infrastructure for water will most likely increase, driving decreases in the water resources available for use in country. On the other hand, simulation of the REMO 0406 scenario indicated there will be no significant trend in annual precipitation in future, but monthly precipitation will vary dramatically. Changes of temperature and precipitation will lead to a decline in runoff of the Amu Darya River and its tributaries. The Amu Darya River will have the largest reduction of runoff in July (2016–2055), up to 1.35×10^9 m^3/year, followed by June (0.69×10^9 m^3/year) and August (0.46×10^9 m^3/year). The reduction of average flow for the growing season (2016–2055) will be about 5 and 6% for the Vakhsh and the Pyanj River, respectively (Dukhovniy, 2018), which will likely cause declining water availability in the Amu Darya River, potentially interrupting the water supply to agriculture to provide for residential use in Turkmenistan. Eventually, disruptions to agricultural production caused by climate change will have negative impacts for the food security of Turkmenistan.

Although climate change will have an adverse impact on the water-climate-food security nexus in Turkmenistan, technological innovations may mitigate or even eliminate climatic risks in water-climate-food security (Smithers and Blay-Palmer, 2001). In Turkmenistan, water resources in the local oasis areas are mainly supplied by a wide-set of networks of irrigation canals and drainage systems, the most famous of which is the Karakum Canal, the world's longest irrigation and supply waterway (1370 km) (Baker, 2018). Due to the low level of technical capacity, however, these irrigation systems waste a great deal of water during irrigation of agricultural crops and lead to the loss or degradation of fertile lands, degradation of rivers and other environmental consequences (Zonn et al., 2018). In response, some work has been done to support and develop innovative technologies in Turkmenistan, which will likely be enhanced in future (Garabayeva, 2012; Zonn and Kostianoy, 2014). Hence, we included an innovation scenario for this study, offsetting the negative impacts from changes in precipitation patterns and rising temperatures (see Table 1).

Design and selection of scenarios is a challenge in projecting future water resources (Daher and Mohtar, 2015; Karan et al., 2018; Mohtar and Daher, 2014; Duan et al., 2017b). Turkmenistan is an agrarian economy, and the agricultural sector is a prominent sector,

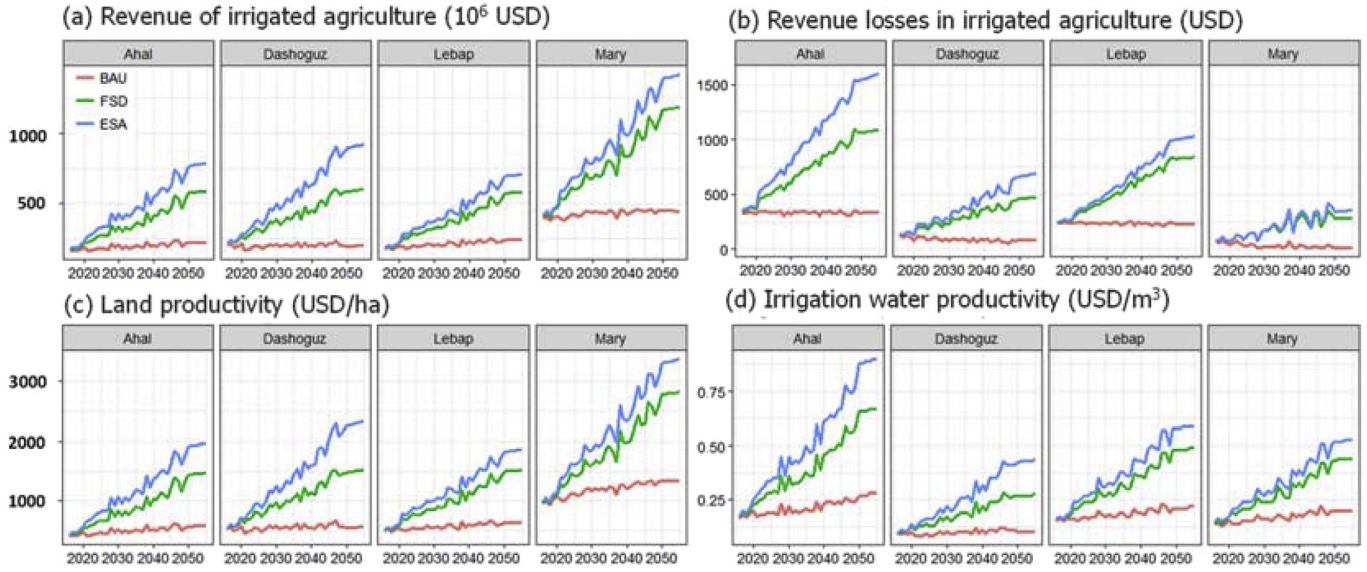

Fig. 9. Time series of (a) revenue of irrigated agriculture (10^6 USD), (b) revenue losses in irrigated agriculture (USD), (c) land productivity (USD/ha), and (d) irrigation water productivity (USD/m^3) for four provinces in Turkmenistan from 2016 to 2055.

Table 3
Land and water productivity in Turkmenistan under different scenarios.

Scenario	BAU				FSD			ESA		
Year	2015	2020	2040	2055	2020	2040	2055	2020	2040	2055
Revenue of irrigated agriculture (10^8 USD)										
Ahal	3.87	1.94	2.03	2.24	2.22	4.17	5.88	2.34	5.52	7.87
Dashoguz	4.36	2.12	1.99	1.98	2.76	4.5	6.03	2.85	6.33	9.21
Lebap	3.99	1.93	2.27	2.44	2.14	4.34	5.81	2.21	5.19	7.06
Mary	6.55	4.11	4.24	4.45	4.73	8.36	11.8	4.86	9.84	14.2
Revenue losses in irrigated agriculture (USD)										
Ahal	283.54	316.3	334.56	335.57	362.34	846.07	1083.19	378.55	1170.37	1595.17
Dashoguz	40.45	79.11	86.91	80.51	126.17	361.98	470.67	129.47	492.54	689.32
Lebap	32.68	234.83	228.48	232.17	267.98	626.02	836.53	272.88	727.42	1030.13
Mary	26.86	39.44	40.44	13.59	77.12	294.34	283.08	77.85	331.86	354.39
Land productivity (USD/ha)										
Ahal	704.91	487.5	523	584.65	546.33	1037.68	1469.6	576.57	1371.91	1968.02
Dashoguz	1110.49	578.81	555.9	561.34	692.57	1135.86	1526.52	714.37	1597.62	2331.11
Lebap	1114.25	531.52	606.89	636.62	585.56	1153.63	1521.27	604.37	1383.59	1864.72
Mary	1125.28	1066.04	1204.53	1344.02	1113.72	1982.28	2813.67	1145.45	2335.46	3373.65
Irrigation water productivity (USD/m^3)										
Ahal	0.23	0.2	0.23	0.28	0.23	0.46	0.67	0.25	0.61	0.9
Dashoguz	0.12	0.1	0.11	0.1	0.13	0.22	0.28	0.14	0.32	0.44
Lebap	0.18	0.16	0.19	0.22	0.18	0.36	0.49	0.19	0.43	0.59
Mary	0.19	0.15	0.18	0.2	0.17	0.33	0.44	0.17	0.39	0.53

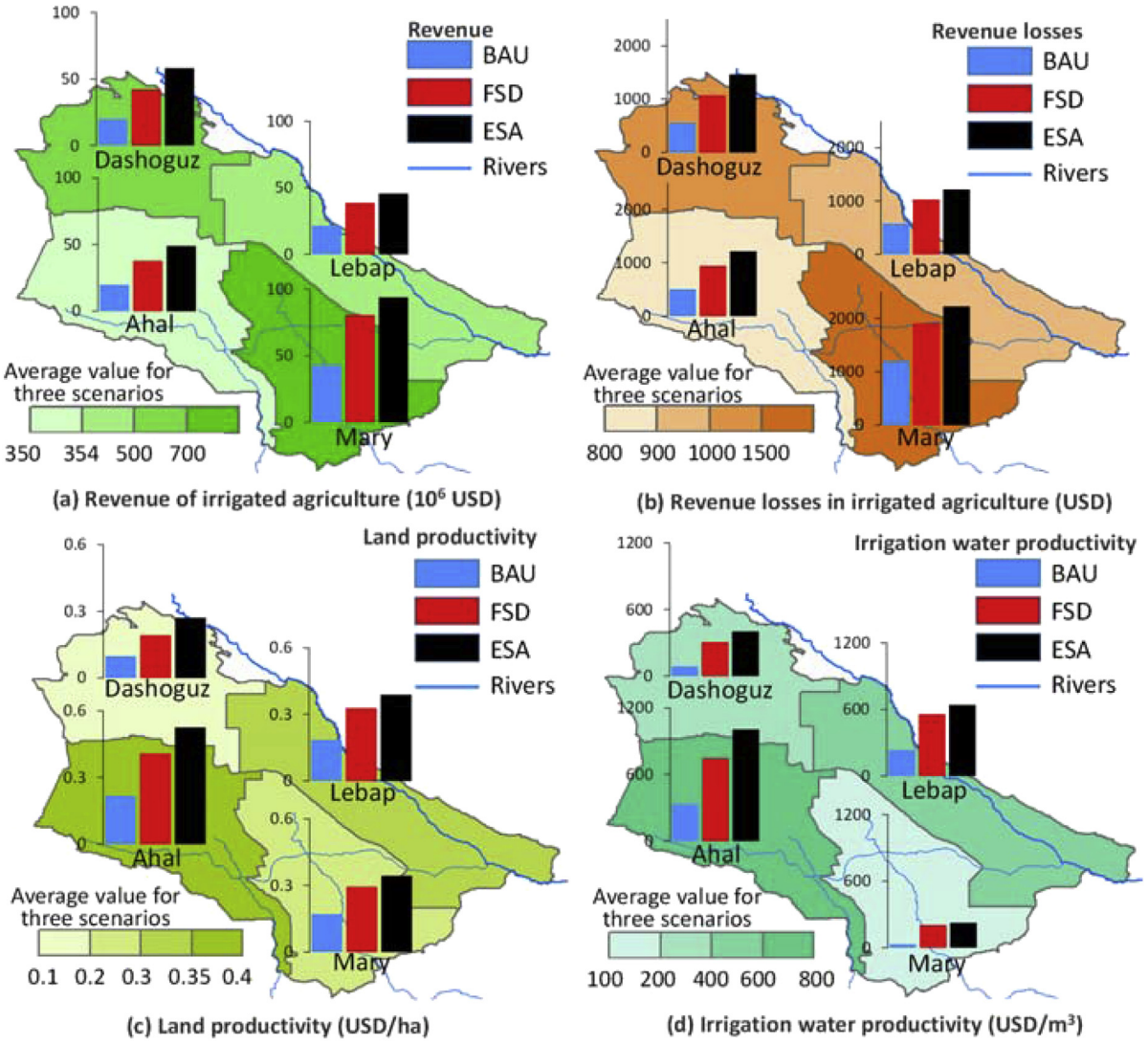

Fig. 10. The estimated averaged annual (a) revenue of irrigated agriculture (10^6 USD), (b) revenue losses in irrigated agriculture (USD), (c) land productivity (USD/ha), and (d) irrigation water productivity (USD/m^3) under BAU, FSD, and ESA scenarios for four provinces in Turkmenistan from 2016 to 2055.

reflecting 58% of the rural population and 48% of the total labor force (Lerman et al., 2012). Additionally, water and land are precious resources contributing to food production in Turkmenistan (Zonn and Kostianoy, 2014). The BAU scenario is therefore clearly inappropriate for future development under climate change and the development of the external economy (the external economies of scale occur based on larger changes outside of the country). The FSD scenario was used to maximize food production for self-sufficiency. The ESA scenario generally met 80% of food self-sufficiency while maximizing food exports. According to population growth and economic development, we can determine the optimization criteria to optimize the crop mix. Furthermore, the increase of agricultural export potential will bring innovative water and resource-saving technologies, eventually contributing to improving land and water productivities.

Finally, limitation and uncertainty analysis is necessary. It is evident that climate models have some degree of uncertainty about future precipitation and temperature prediction, likely affecting our ability to evaluate crop water requirements during growing seasons (Knutti and Sedláček, 2013). Difficulty in evaluating runoff from the glacial shrinking in the high mountain ranges of Pamir and Tien Shan under climate change (Sorg et al., 2012) introduce another source of uncertainty in estimating river discharge for the Amu Darya River, which directly affects the water withdrawal limit from transboundary sources in Turkmenistan, although 50% of the coefficient was selected in this study. Furthermore, incomplete historical datasets, notably from Afghanistan, introduce yet another uncertainty into the modeling via ASBmm. These uncertainties reflect another limitation to the accuracy of our projections.

5. Conclusions and suggestions

This study describes synthetic estimates of water requirements and water deficits for irrigation, future agricultural yields of seven major crops, and land and water productivity in four provinces of Turkmenistan for the period 2016–2055 considering climate change, population growth, and three socio-economic development scenarios (BAU, FSD, and ESA). Results indicate that: (1) Changes in precipitation patterns and rising temperatures caused by climate change are expected to exacerbate the challenges of meeting needs of the water-climate- food security nexus in Turkmenistan; (2) Water requirements and deficits during the growing seasons exhibit a decreasing trend from 2016 to 2055 in most provinces under the BAU, FSD, and ESA scenarios, and the largest provinces for water requirements and water deficits were Dashoguz and Ahal province, respectively; (3) Production of seven major crops, cotton, wheat, rice, maize, vegetables, orchards, and forage, were predicted to increase during the study period for the four provinces under both the FSD and ESA scenarios; (4) Land and water productivity were projected to increase from 2016 to 2055 for all four provinces under the FSD and ESA scenarios; and (5) Mary province will have the highest mean income and losses of irrigated agriculture for the three scenarios, at 7×10^8 USD/year and 1.50×10^3 USD/year respectively, and Ahal province will have the largest mean land and irrigation water productivities for three scenarios, at 800 USD/ha/year and 0.40 USD/m^3/year, respectively.

Results obtained from this study provide valuable information and tools that will help Turkmenistan's government manage the nexus of water, land and energy resources to ensure future food security and sustainable socio-economic development. It is important to note that several assumptions (e.g., the 50% water withdrawal limit from transboundary sources, innovative irrigation techniques.) were used in this study. Future progress in sustainable resource management in Central Asia will require (1) an updated legal framework for managing transboundary water resources; (2) development of an integrated basin management plan for the Amu Darya River Basin for optimal management of hydropower, irrigated agriculture and aquatic ecosystems; and (3) increased investments in national water sectors including agricultural techniques, irrigation networks and technologies. Therefore, in the future work, more detailed conditions should be also considered in the water–climate-food security nexus for the whole Amu Darya River Basin.

Acknowledgements

This study is sponsored by the Strategic Priority Research Program of the Chinese Academy of Sciences (Grant No. XDA19030204), the Pioneer “Hundred Talents Program” of the Chinese Academy of Sciences, the National Natural Science Foundation of China (No. 41501552, 41630859), and the Talent Introduction Project of Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences. We also wish to acknowledge Prof. Viktor A. Dukhovniy for his kind help when running the ASBmm.

The authors declare that they have no conflicts of interest in the research.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.02.040.

References

Akhtar, F., Tischbein, B., Awan, U.K., 2013. Optimizing deficit irrigation scheduling under shallow groundwater conditions in lower reaches of Amu Darya River Basin. Water Resour. Manag. 27, 3165–3178.
Aleksandrova, M., 2015. Water Scarcity under Climate Change: Impacts, Vulnerability and Risk Reduction in the Agricultural Regions of Central Asia. Ph.D, Ca'Foscari University of Venice.
AQUASTAT, 2016. FAO's Information System on Water and Agriculture accessed July 2018. www.fao.org.
Baker, B.E., 2018. The hydrosocial empire: the Karakum River and the soviet conquest of central asia in the 20th century. J. Anthropol. Archaeol. 52, 123–136.
Bekchanov, M., Ringler, C., Bhaduri, A., Jeuland, M., 2016. Optimizing irrigation efficiency improvements in the Aral Sea basin. Water Resources and Economics 13, 30–45.
Bekchanov, M.B., 2014. Efficient Water Allocation and Water Conservation Policy Modeling in the Aral Sea Basin. Ph.D.
Bekturganov, Z., Tussupova, K., Berndtsson, R., Sharapatova, N., Aryngazin, K., Zhanasova, M., 2016. Water related health problems in central asia—a review. Water Sui. 8, 219.
Bernauer, T., Siegfried, T., 2012. Climate change and international water conflict in Central Asia. J. Peace Res. 49, 227–239.
Chmielewski, F.M., Muller, A., Bruns, E., 2004. Climate changes and trends in phenology of fruit trees and field crops in Germany, 1961-2000. Agric. For. Meteorol. 121, 69–78.
Clay, J., 2011. Freeze the footprint of food. Nature 475, 287–289.
Conway, D., Garderen, E.A.V., Deryng, D., Dorling, S., Krueger, T., Landman, W., Lankford, B., Lebek, K., Osborn, T., Ringler, C., 2015. Climate and southern Africa's water-energy-food nexus. Lse Research Online Documents on Economics 5, 837–846.
Daher, Mohtar, 2015. Water–energy–food (WEF) Nexus Tool 2.0: guiding integrative resource planning and decision-making. Water Int. 40, 748–771.
Dai, J., Wu, S., Han, G., Weinberg, J., Xie, X., Wu, X., Song, X., Jia, B., Xue, W., Yang, Q., 2018. Water-energy nexus: a review of methods and tools for macro-assessment. Appl. Energy 210, 393–408.
De Schutter, J., 2008. Communicating the Issues of the Aral Sea Basin Long-Term Vision or the Aral Sea Basin the Aral Sea Basin Management Model (ASBMM)., Transboundary Water Resources: a Foundation for Regional Stability in Central Asia. Springer, pp. 29–42.
DeNooyer, T.A., Peschel, J.M., Zhang, Z., Stillwell, A.S., 2016. Integrating water resources and power generation: the energy–water nexus in Illinois. Appl. Energy 162, 363–371.
Duan, W., He, B., Sahu, N., Luo, P., Nover, D., Hu, M., Takara, K., 2017a. Spatiotemporal variability of Hokkaido's seasonal precipitation in recent decades and connection to water vapour flux. Int. J. Climatol. 37, 3660–3673.
Duan, W., He, B., Takara, K., Luo, P., Nover, D., Hu, M., 2017b. Impacts of climate change on the hydro-climatology of the upper Ishikari river basin, Japan. Environ. Earth Sci. 76 (14), 490.

Dukhovniy, V.A., 2018. Transboundary Water Management Adaptation in the Amudarya Basin to Climate Change Uncertainties accessed August 2018. http://www.cawater-info.net.
Ellabban, O., Abu-Rub, H., Blaabjerg, F., 2014. Renewable energy resources: current status, future prospects and their enabling technology. Renew. Sustain. Energy Rev. 39, 748–764.
Elliott, J., Deryng, D., Müller, C., Frieler, K., Konzmann, M., Gerten, D., Glotter, M., Flörke, M., Wada, Y., Best, N., 2014. Constraints and potentials of future irrigation water availability on agricultural production under climate change. Proc. Natl. Acad. Sci. Unit. States Am. 111, 3239–3244.
Farinotti, D., Longuevergne, L., Moholdt, G., Duethmann, D., Mölg, T., Bolch, T., Vorogushyn, S., Güntner, A., 2015. Substantial glacier mass loss in the Tien Shan over the past 50 years. Nat. Geosci. 8, 716.
Food and Agriculture Organization, 2009. Global Agriculture towards 2050 (Rome, 2009) accessed August 2018. http://www.fao.org/fileadmin/templates/wsfs/docs/Issues_papers/HLEF2050_Global_Agriculture.pdf.
Garabayeva, B., 2012. National Program of Turkmenistan on Socio-Economic Development for the Period 2011-2030 accessed July 2018. https://ims.undg.org/downloadFile/a303c0f7855ef9a8cceec3133577fd61b594acd58284b04098da77e65f63a6e3.
Godfray, H.C., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., Toulmin, C., 2010. Food security: the challenge of feeding 9 billion people. Science 327, 812.
Granit, J., Jägerskog, A., Lindström, A., Björklund, G., Bullock, A., Löfgren, R., de Gooijer, G., Pettigrew, S., 2012. Regional options for addressing the water, energy and food nexus in Central Asia and the Aral Sea Basin. Int. J. Water Resour. Dev. 28, 419–432.
Harvey, M., Pilgrim, S., Lawrence, D., Beddington, S.J., Godfray, C., Crute, I., Haddad, L., Muir, J., Pretty, J., Robinson, S., 2011. The new competition for land: food, energy, and climate change. Food Policy 36, S40–S51.
Howells, M., Hermann, S., Welsch, M., Bazilian, M., Alfstad, T., Gielen, D., Rogner, H., Fischer, G., 2013. Integrated analysis of climate change, land-use, energy and water strategies. Nat. Clim. Change 3, 621–626.
IEA, 2016. World Energy Outlook 2016 accessed August 2018. https://www.iea.org/publications/freepublications/publication/WorldEnergyOutlook2016ExecutiveSummaryEnglish.pdf.
Jalilov, S., Amer, S.A., Ward, F.A., 2018. Managing the water-energy-food nexus: opportunities in central asia. J. Hydrol. 557, 407–425.
Jalilov, S., Keskinen, M., Varis, O., Amer, S., Ward, F.A., 2016. Managing the water–energy–food nexus: gains and losses from new water development in Amu Darya River Basin. J. Hydrol. 539, 648–661.
Kaplan, S., Blumberg, D.G., Mamedov, E., Orlovsky, L., 2014. Land-use change and land degradation in Turkmenistan in the post-Soviet era. J. Arid Environ. 103, 96–106.
Karan, E., Asadi, S., Mohtar, R., Baawain, M., 2018. Towards the optimization of sustainable food-energy-water systems: a stochastic approach. J. Clean. Prod. 171, 662–674.
Kendall, M.G., 1975. Rank Correlation Methods. Charles Griffin., London.
Knutti, R., Sedláček, J., 2013. Robustness and uncertainties in the new CMIP5 climate model projections. Nat. Clim. Change 3, 369–373.
Kostianoy, A.G., Lebedev, S.A., Solovyov, D.M., 2011. Satellite monitoring of water resources in Turkmenistan. Int Water Technol J 1, 4–15.
Lerman, Z., Prikhodko, D., Punda, I., Sedik, D., Serova, E., Swinnen, J., 2012. Turkmenistan Agricultural Sector Review accessed August 2018. http://www.fao.org/3/a-i2911e.pdf.
Li, J., Li, Z., Zhu, J., Li, X., Xu, B., Wang, Q., Huang, C., Hu, J., 2017. Early 21st century glacier thickness changes in the Central Tien Shan. Remote Sens. Environ. 192, 12–29.
Liu, J., Mao, G., Hoekstra, A.Y., Wang, H., Wang, J., Zheng, C., Vliet, M.T.H.V., Wu, M., Ruddell, B., Yan, J., 2018. Managing the energy-water-food nexus for sustainable development. Appl. Energy 210, 377–381.
Malsy, M., Aus Der Beek, T., Eisner, S., Flörke, M., 2012. Climate change impacts on Central Asian water resources. Adv. Geosci. 32, 77–83.
Mann, H.B., 1945. Nonparametric tests against trend. Econometrica 13, 245–259.
Merks, J., 2018. The Water Efficiency Paradox: the Significance of Spatial Scale and Knowledge Exchange in Irrigation Water Management. Master. Delft University of Technology.
Mohtar, R.H., Daher, B., 2014. A Platform for Trade-Off Analysis and Resource Allocation: the Water-Energy-Food Nexus Tool and its Application to Qatar's Food Security [part of the 'Valuing Vital Resources in the Gulf'Series]. Chatham House (2014).
Mohtar, R.H., Daher, B., 2015. Water–energy–food (WEF) Nexus Tool 2.0: guiding integrative resource planning and decision-making. Water Int. 40, 748–771.
Mohtar, R.H., Shafiezadeh, H., Blake, J., Daher, B., 2019. Economic, social, and environmental evaluation of energy development in the Eagle Ford shale play. Sci. Total Environ. 646, 1601–1614.
Mortada, S., Najm, M.A., Yassine, A., Fadel, M.E., Alamiddine, I., 2018. Towards sustainable water-food nexus: an optimization approach. J. Clean. Prod. 178, 408–418.
Peã Uelas, J., Rutishauser, T., Filella, I., 2009. Ecology. Phenology feedbacks on climate change. Science 324, 887–888.
Rakhmatullaev, S., Abdullaev, I., Kazbekov, J., 2017. Water-Energy-Food-Environmental Nexus in Central Asia: from Transition to Transformation.
Schewe, J., Heinke, J., Gerten, D., Haddeland, I., Arnell, N.W., Clark, D.B., Dankers, R., Eisner, S., Fekete, B.M., ColÃ N-GonzÃ Lez, F.J., 2014. Multimodel assessment of water scarcity under climate change. Proc. Natl. Acad. Sci. U. S. A. 111, 3245–3250.
Smajgl, A., Ward, J., Pluschke, L., 2016. The water–food–energy Nexus – realising a new paradigm. J. Hydrol. 533, 533–540.
Smithers, J., Blay-Palmer, A., 2001. Technology innovation as a strategy for climate adaptation in agriculture. Appl. Geogr. 21, 175–197.
Sorg, A., Bolch, T., Stoffel, M., Solomina, O., Beniston, M., 2012. Climate change impacts on glaciers and runoff in Tien Shan (Central Asia). Nat. Clim. Change 2, 725.
Stanchin, I., Lerman, Z., 2017. Wheat Production in Turkmenistan: Reality and Expectations., the Eurasian Wheat Belt and Food Security. Springer, pp. 215–228.
Wang, H.L., Gan, Y.T., Wang, R.Y., Niu, J.Y., Zhao, H., Yang, Q.G., Li, G.C., 2008. Phenological trends in winter wheat and spring cotton in response to climate changes in northwest China. Agric. For. Meteorol. 148, 1242–1251.
Yue, S., Pilon, P., Cavadias, G., 2002. Power of the Mann–Kendall and Spearman's rho tests for detecting monotonic trends in hydrological series. J. Hydrol. 259, 254–271.
Zonn, I.S., Kostianoy, A.G., 2014. The Turkmen Lake Altyn Asyr and Water Resources in Turkmenistan. Springer Berlin Heidelberg.
Zonn, I.S., Kostianoy, A.G., Lokteva, T.V., Shtol, V.V., 2018. Turkmenistan water resources policy in central asia. In: The Handbook of Environmental Chemistry. Springer, Berlin, Heidelberg.